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Designing Cost-Effective Reliable Networks From a Risk Analysis Perspective: A Case Study for a Hospital Campus

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ABSTRACT The unavailability of information and communication services due to network-related incidents may have a significant impact on large organizations. Network incidents can hence be viewed as a risk for organizations whose consequences are not accounted for by traditional network design problems. In this work, we address the problem of designing a reliable wired network from a risk analysis perspective. We propose a novel methodology for the quantitative assessment of the risk associated with network-related incidents in a hospital campus. We then define an optimization problem to find the topology that minimizes the network cost plus the expected loss over time attributable to the unavailability of corporate services to staff affected by network incidents. A case study illustrates our methodology and its benefits. Using available public information, we design the topology of a campus network for a large hospital where the cost of labor exceeds 200 M€/year. The solution to our optimization problem is found through well-known genetic algorithms and provides a topology where network nodes with a higher impact on productivity exhibit higher reliability. As a consequence, the topology obtained reduces more than 95% (+392 000€) the expected annual lost profits when compared to common reduced-cost topologies such as the minimum-cost ring or the non-reliable minimum-cost tree, showing that investment in risk reduction pays off. Our contribution may be used by engineers to (re)design cost-effective reliable networks or by hospital managers to support decisions on updating present infrastructure based on risk reduction.

INDEX TERMS Network topology design, reliability, risk analysis.

I. INTRODUCTION

Wired data networks are critical enablers of Information and Communication Technology (ICT) services, which in turn bring financial benefits to organizations in the form of productivity improvement or competitive differentiation [1]. Hospitals have become critically dependent on ICT services as they support most of their business processes despite their clinical (e.g., patient management, electronic medical records, pharmacy, etc.), managerial (e.g., human resources, payrolls, supply management, inventory, etc.), or strategic (e.g., providing information support for long-term planning) nature [2]. The adoption of these services has facilitated managerial outcomes such as improving the quality of patient care [3] but primarily, reducing operational costs [4], [5]. As such, degraded or disrupted ICT services have a substantial impact on people, processes, and business goals [6], [7].

At a physical level, a wired data network is made up of nodes (e.g., packet switches) interconnected by communication links. These assets are exposed to threats such as natural disasters, power outages, accidental damage, cyberattacks, etc. When threats materialize, network service is degraded and ICT services may become unavailable to some users, impacting operational performance, which represents a risk for the organization. Figure 1 illustrates an example data network where hospital workers access ICT services delivered from a local or remote data center accessible through a central network node (root). If the link between nodes 1 and 2 suffered accidental damage, users attached to nodes 2 and 3 would lose network connectivity and therefore, access to ICT services. While some activities may remain unaffected, some others would revert to slower, manual procedures. After recovery, the affected information systems

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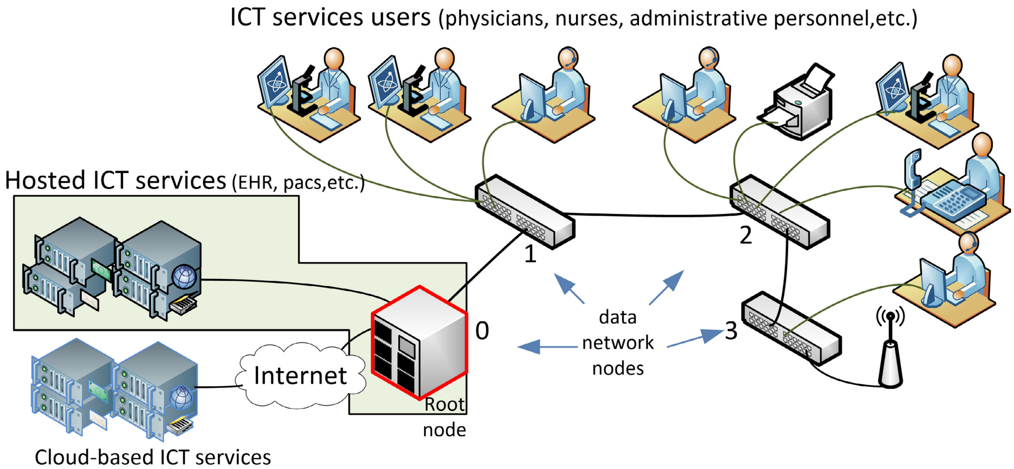

FIGURE 1. Example of data network topology and the use of ICT services.

would have to be checked and updated for the sake of consistency [8]. This overall process would likely result in a degraded quality of patient care and operational struggle, not to mention reputation and economic costs.

A countermeasure to reduce degradation in the previous example is to create alternative paths in the network topology by adding extra links. For example, a link between nodes 0 and 3 in Figure 1 would create a ring topology that would withstand the failure of one link as switches can autonomously re-arrange packet forwarding at the link-layer. Thus, the new link added to the baseline topology can be viewed as a countermeasure that reduces the risk of staff unable to do their job at full capacity and its associated impact. However, implementing this countermeasure also implies cost and it is unclear as to whether such an investment would pay off. This work addresses the challenge of finding the topology with the most profitable redundancy (viewed as an investment). However, as commonly considered in the field of cybersecurity, the return of investment does not translate to increased revenues but rather loss prevention (i.e. reduction of risk).

The design of reliable networks is a mature topic in engineering [9]. Given a set of nodes, the reliable network design problem either finds the minimum cost topology subject to a reliability constraint [10] or the most reliable topology subject to a cost constraint [11]. Unfortunately, reliability is typically expressed in terms of the probability that network nodes are fully interconnected (e.g., 0.994) which is not as meaningful for an organization as the impact of the unavailability of ICT services on business processes.

In this paper, we propose a methodology for designing a reliable wired data network in the context of a hospital campus. Given a set of nodes with known location and some basic information from the organization, we provide a method for estimating per node loss expectancy attributable to users unable to access ICT services due to loss of network connectivity. This information is then used to obtain the most profitable topology with minimum investment. A case study will apply this methodology to the design of the data network of a large hospital campus in Seville (Spain), showing the benefits of our proposal compared to traditional generic methods.

The novelty and originality of this work are:

- We frame network design into the field of risk analysis.
- We develop a simple but efficient model of the impact of network downtime in productivity for the healthcare environment.
- We provide a network design methodology that optimizes the return of the investment.

The contributions of this paper can be used for planning the data network of new hospitals or for upgrading/extending current networks. Note that the scope of this paper is restricted to the wired network, excluding other systems such as wireless networks, or software protocols implemented at network nodes which can also impact connectivity.

The remainder of this paper is organized as follows. Section II provides an overview of related works. Section III defines the optimization problem, which is based on the reliability and loss expectancy models defined in Section IV. Section V briefly introduces the heuristic method used to find solutions. A case study is presented in Section VI and the results obtained in Section VII. Finally, Section VIII concludes the paper.

II. RELATED WORKS

The role of ICT in healthcare has been comprehensively addressed in [12], where more than 300 papers from both technological and medical fields are reviewed. *Aceto et al.* use a 3-layer model to dissect scientific literature. At the bottom layer, wired and wireless networks and other technologies such as smart devices form the *ICT pillars*. The middle layer comprises *ICT paradigms* such as cloud computing or IoT, and the third layer includes current *ICT-based healthcare paradigms* such as e-health, mobile health, or ubiquitous health. Today, most of the research interest is focused on the top two layers, and from the bottom layer, only wireless networks have received some attention for providing ad-hoc infrastructure for emergencies [13], bringing clinical information to the point of care [14], or collecting clinical data from remote patients for e-health applications [15], [16]. Despite being a critical part of *ICT pillars*, literature specifically targeted to the design of wired networks in healthcare environments is both scarce and outdated [17]–[19]. As such, it is implicitly assumed to be a subject that can either be successfully addressed with proprietary knowledge or sufficiently covered by generic problems defined in the scientific literature.

A. RELIABLE NETWORK DESIGN PROBLEMS

Many network design problems have been addressed in literature over several decades [20]–[22], but the design of reliable networks is rooted in the Reliable Network Design (RND) problem [23], [24]. Given a set of nodes, this optimization problem typically finds the set of links that either minimizes the cost of building a network subject to reliability (i.e. the probability that the graph is still connected even if some of the edges fail) [10], [25], [26], or maximizes reliability subject to cost. A good example can be found in [11], where the authors design a reliable campus-wide network interconnecting 11 nodes (which represent buildings at Gazi University) and compare the performance of various metaheuristics in finding optimal solutions. Solutions are presented comparing the network topology cost versus its associated reliability. However, in our context, three main objections can be made: (i) the reliability model used is all-terminal (i.e. probability that all nodes are interconnected) whereas in a centralized local area network such as the one illustrated in Figure 1, the access to ICT services depends on the availability of a physical path to the root node (two-terminal reliability [27]); (ii) the impact of network incidents (which is more meaningful than a simple probability) is ignored; (iii) in the optimization problem all nodes are assumed to be equally important for the organization whereas in practice the consequences of node failure may be different depending on users affected as shown in the previous section. To the best of our knowledge, only the Productivity-Aware RND problem [28] envisages the impact of network incidents in terms of economic cost but unfortunately, it does not specify how to model such impact.

B. IMPACT OF NETWORK DOWNTIME IN HOSPITALS

Health ICT outages and its implications have been studied in [29], where 116 hospital incident reports in China have been examined. The top three factors that caused outages were software malfunction, hardware malfunction, and loss of network connectivity. The time of the day where incidents occurred was predominantly in the morning shift. The patient care areas most affected were outpatient, billing, and pharmacy: the entire hospital was affected in eight cases. The negative outcomes included patient care affected (e.g., risks, canceled visits, etc.) but also financial losses (35 cases) in the form of lawsuits, monetary compensations, and opportunity costs associated with patient care services during ICT outage. None of the incident reports provided an explicit estimation of the magnitude of the financial losses.

Cost of communication inefficiencies has also been explored in [30]. The authors point out that outages in communication services are a common cause of wasted time for physicians and nurses, increasing the stay for inpatients. Their survey indicates that physicians and nurses waste 2% and 8% of their shift time respectively, accounting for estimated losses of up to $4 million annually for a typical 500-bed hospital in the U.S. In [31], the author finds that for every minute an Electronic Health Record (EHR) application is down, the average physician spends 2.15 minutes to perform the required task manually, plus the time required to update the computer system after recovery. Nurses also spend additional time in performing tasks. This does not take into account the cost of improper or erroneous diagnosis and prescriptions due to outdated information in the EHR but provides a lower bound on network outage costs.

In general, assessing the economic impact of ICT in healthcare is a difficult task which requires methods to account for the economic return of the investment [32], such as cost-effectiveness analysis, cost-benefit analysis, and cost-utility analysis [33]. However, econometric methods address the output of using ICT and not its relation with the network infrastructure that supports ICT services.

From our review of literature one can conclude that while it is proven that network incidents result in time wasted by staff, its translation to economic cost usable into a network design problem has never been addressed before. This is not a trivial task and should be organization specific. However, we believe that a basic but effective model can be applied to healthcare organizations enabling the design of their data networks based on risk reduction.

III. PROBLEM STATEMENT

As introduced earlier, the value of a data network can be observed from a risk analysis perspective: nodes and communication links are assets vulnerable to threats such as accidental breakage, power failure, etc. that materialize with a certain probability causing degradation in the asset (i.e. disconnection of some network nodes resulting in outage of ICT services for affected users). The risk associated with a wired data network can then be calculated through the classical formula:

$$\text{Risk} = P \times I \tag{1}$$

where P stands for the frequency of occurrence of the threat, and I accounts for estimation of the impact for the organization which can be quantified in terms of lost profits as a result of time wasted by affected staff.

In our context, each possible network topology with alternative paths to the root node can be seen as a countermeasure for risk mitigation. Clearly, a full-mesh topology exhibits higher resilience to accidental failures than a tree-like topology. However, it also requires higher investment (i.e. capital expenditure or CAPEX). Thus, the question at hand is: which topology is the best investment?

A. BENEFITS OF INVESTMENTS IN COUNTERMEASURES

In the field of cybersecurity, investment in countermeasures is not expected to return revenues but loss prevention.[1] The following definitions are typically applied in risk analysis:

- Single Loss Expectancy (SLE): is the expected amount of money that is lost during a single incident. It is difficult to estimate and it should include at least direct loss costs and indirect costs associated with fallout of the data breach.
- Annual Loss Expectancy (ALE) $= SLE \times ARO$, where ARO stands for Annual Rate of Occurrence (i.e. probability of having an incident in one year). This is equivalent to risk.
- Modified Annual Loss Expectancy ($mALE$) is similar to ALE but includes (i.e. subtracts) the loss prevented by the implemented countermeasure. This is equivalent to residual risk after implementing the countermeasure.

Therefore, the Annual Loss Prevention (ALP) attributable to a countermeasure can be expressed as $ALP = ALE - mALE$.

The benefit of investing in a countermeasure can be evaluated through the Net Present Value (NPV). The NPV compares anticipated benefits and cost over time, discounting investment and cost over time to the present value. It can be defined as:

$$NPV(T) = -CAPEX + \sum_{i=1}^{T} \frac{ALP_i - C_i}{(1+k)^i} \tag{2}$$

where $CAPEX$ is the cost of building the network topology, T is the period over which the investment is evaluated, C_i is the annual cost, and k is the annual discount rate. It seems evident that any countermeasure should meet $NPV > 0$ to be eligible.

Let $\boldsymbol{x}$ be a network topology with redundant paths to the root node which can be used as a potential countermeasure in our context. Then, the most profitable network topology over the period T is the $\boldsymbol{x}$ that maximizes $NPV(\boldsymbol{x}, T)$:

$$\max\ NPV(\boldsymbol{x}, T) = \max \left(-CAPEX(\boldsymbol{x}) + \sum_{i=1}^{T} \frac{ALE - mALE_i(\boldsymbol{x}) - C_i}{(1+k)^i} \right) \tag{3}$$

For the remainder of this paper, we assume that:

- A physical topology does not require operation expenditure (i.e. $C_i = 0$ in Equation 3).
- $mALE$ is constant over the T years under consideration (i.e. $mALE_i = mALE, \forall i$ in in Equation 3).
- ALE (i.e. annual loss expectancy before the countermeasure) does not depend on $\boldsymbol{x}$

Then, the condition expressed in Equation 3 is equivalent to:

$$\min \left(CAPEX(\boldsymbol{x}) + mALE(\boldsymbol{x}) \sum_{j=1}^{T} \frac{1}{(1+k)^j} \right) \tag{4}$$

Let us define the modified loss expectancy after T years, $mLE(x, T)$ as:

$$mLE(x, T) = mALE(\boldsymbol{x}) \sum_{j=1}^{T} \frac{1}{(1+k)^j} \tag{5}$$

Then, the most beneficial topology $\boldsymbol{x}$ after T years is the one that minimizes the sum of the cost of building the network plus its associated modified loss expectancy:

$$\min\ (CAPEX(\boldsymbol{x}) + mLE(\boldsymbol{x}, T)) \tag{6}$$

B. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

A communication network can be modeled by a probabilistic graph $G = (N, L, p_n, p_l)$ in which N and L are the set of nodes and communication links respectively, p_n is the reliability of the nodes (i.e. probability that it is operational) and p_l is the reliability of communication links per length unit.

Let us define CAPEX of a network $\boldsymbol{x}$ as:

$$CAPEX(\boldsymbol{x}) = \sum_{i=1}^{|N|} \sum_{j=1}^{|N|-1} c_{ij} x_{ij} \tag{7}$$

where $x_{ij} \in \{0, 1\}$ is a boolean variable that indicates whether (i, j) link exists or not, and c_{ij} is the cost of (i, j) link. Note that although cost can be further modeled using the link's length and type such as in [11], we assume that cost information is given. Furthermore, in a topology re-design c_{ij} should be 0 for those communication links that already exist. This would also allow one to verify that the cost of the countermeasure is less than the expected return (i.e. $mLE > CAPEX$).

Then, taking x_{ij} as the decision variable, the optimization problem that finds the most beneficial topology after T years of network operation can be formulated as:

$$\underset{x_{ij}}{Minimize} \left(\sum_{i=1}^{|N|} \sum_{j=1}^{|N|-1} c_{ij} x_{ij} + mLE(\boldsymbol{x}, T) \right) \tag{8}$$

The problem assumptions are:

- Networks have bidirectional links and therefore are modeled by graphs with nondirected links. It is further assumed that the graph is connected and has no parallel (i.e., redundant) edges.
- The location and number of nodes are known.
- Each c_{ij}, p_n, p_l, k and T are fixed and known.
- Failures are assumed to be independent and components can only take one of two states, operational or failed.

[1] This is equivalent to opportunity cost, or alternative cost in microeconomic theory (i.e. the most valuable choice).

- A root node $\in N$ interconnect servers (either local or remote) to the network. This node is assumed to be perfectly reliable. This assumption is based on the fact that data centers are typically well conditioned and secured. Furthermore, if the root node fails, ICT services become unavailable to all users. As such, the topology of the network becomes irrelevant as no risk reduction can be achieved through topology design.

Finally, bandwidth in the network is assumed to be sufficient for the ICT services provided. This is justified in today's switched Ethernet thanks to high-speed links (1-10 Gbps) and available techniques for traffic segregation and prioritization.

IV. MODELING THE MODIFIED LOSS EXPECTANCY

To fit into the optimization problem, $mLE(\boldsymbol{x}, T)$ has to be apportioned among the nodes of the network. This can be mathematically formulated as:

$$mLE(\boldsymbol{x}, T) = \sum_{j=1}^{T} \frac{mALE(\boldsymbol{x})}{(1+k)^j} = \sum_{j=1}^{T} \frac{24 \times 365}{(1+k)^j} \cdot \sum_{i=1}^{|N|-1} \Gamma_i(\boldsymbol{x})\, S_i \quad (9)$$

where $\Gamma_i(\boldsymbol{x})$ is the probability that node i is disconnected from the root node; S_i represents the expected hourly loss due to the unavailability of network service to users attached to node i. Both factors can be modeled as follows.

A. MODELING $\Gamma_i(\boldsymbol{x})$

$\Gamma_i(\boldsymbol{x})$ accounts for the probability of having no valid path from node i to the root node (two-terminal reliability model). Assuming that both links and nodes can simultaneously fail up to a maximum number (e.g., up to L_F links and N_F nodes), Γ_i can be calculated using the law of total probability (with the simultaneity of failures as mutually exclusive events) as:

$$\Gamma_i(\boldsymbol{x}) = \sum_{l=1}^{L_F} z_{il}\delta_l + \sum_{n=1}^{N_F} w_{in}\gamma_n - \sum_{l=1}^{L_F}\sum_{n=1}^{N_F} z_{il} w_{in} \delta_l \gamma_n \quad (10)$$

where z_{il} is the conditional probability of service outage for node i given that l links have failed simultaneously, δ_l is the probability that l links fail simultaneously, w_{in} is the conditional probability of service outage for node i given that n nodes have failed simultaneously and γ_n is the probability that n nodes fail simultaneously. Further details for the computation of z_{il} and w_{in} can be found in [28].

For example, let G in Figure 2 be the graph representing a specific network topology with 4 nodes (node 0 is root) and 6 links. Let's suppose that up to two nodes and links can simultaneously fail and that the probability node failure is 0.001, and the probability (per meter) of link failure is 10^{-6}. For the sake of simplicity, let's assume that all links exhibit the same length of 100 m. Then, the following values would be obtained:

- probability of simultaneous link failure:
  - single link: $\delta_1 = \binom{6}{1} \cdot 10^{-4} \cdot (1-10^{-4})^5 \simeq 6 \cdot 10^{-4}$
  - two links: $\delta_2 = \binom{6}{2} \cdot 10^{-4 \cdot 2} \cdot (1-10^{-4})^4 \simeq 1.5 \cdot 10^{-7}$

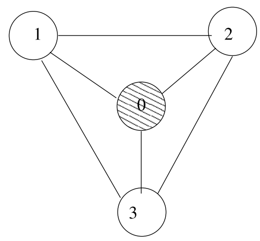

FIGURE 2. Example network *G* (full mesh topology).

- probability of service outage as a result of link failures: (note that each node has three links)
  - when only one link fails: $z_{11} = z_{21} = z_{31} = 0$.
  - when two links fail: $z_{12} = z_{22} = z_{32} = 0$
- probability of simultaneous node failure:
  - single node: $\gamma_1 = \binom{3}{1} \cdot 10^{-3} \cdot (1-10^{-3})^2 \simeq 3 \cdot 10^{-3}$
  - two nodes: $\gamma_2 = \binom{3}{2} \cdot 10^{-3 \cdot 2} \cdot (1-10^{-3}) \simeq 3 \cdot 10^{-6}$
- probability of service outage as a result of node failures:
  - when only one node fails: $w_{11} = w_{21} = w_{31} = 1/3$
  - when two nodes fail: $w_{12} = w_{22} = w_{32} = 2/3$

Substituting the previous probabilities into Equation 10 we obtain: $\Gamma_1(\boldsymbol{x}) = \Gamma_2(\boldsymbol{x}) = \Gamma_3(\boldsymbol{x}) = 0.001$, and the average network reliability would be 0.999. Multiplying $\Gamma_i(\boldsymbol{x})$ by 8 760 hours (24×365), we obtain an expected annual downtime of 8.759 hours for each node.

B. MODELING THE EXPECTED HOURLY LOSS S_i

As stated earlier, losses from network incidents are of many types, including injuries, personal claims, reputation, etc. However, in this work, only the deterioration of productivity will be accounted for. Our approach is based on the idea that workers need extra time to complete tasks when ICT services become unavailable. Then, assuming that salaries are somehow related to productivity, the expected loss related to a network incident can be modeled by a portion of labor cost according to the degradation of performance as a consequence of ICT services unavailability.

Fine-grained modeling of productivity in a hospital can be challenging by itself, not to mention decomposing it into nodes of a network. Note, however, that our goal is not to model how ICT impacts on productivity, but simply to weigh each node of the network according to a rough estimation of how much would be lost if the node was down (i.e. risk). Furthermore, we seek a coarse-grain model simple and generic enough to be valid for most hospital environments.

To assess the risk of each node of the network, we consider a dependency model such as the one illustrated in Figure 3. Its main elements and assumptions are:

- *Nodes* (set N): a network node enables access to ICT services through attached terminals. Node i service is down with probability Γ_i when there is no valid path from node i to the root node. The number of terminals attached to each node and their potential users are known. The root node has no users attached.

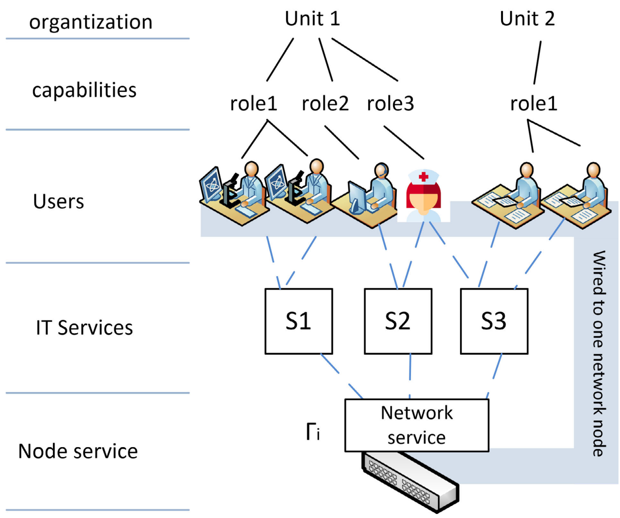

FIGURE 3. Model of dependency between nodes, ICT services, and users.

- *ICT Services*: enhance users productivity and depend on network service. All ICT services are assumed to be accessible from any network node.
- *Users*: each user accesses ICT services through a terminal attached to a network node. As such, users can be apportioned among network nodes accordingly. Each user has a category (i.e. role) and belongs to one organizational unit.
- *Roles*: reflect the capabilities of a worker and determine salary.[2] Users are categorized into roles (see [34] for an exhaustive list). For our purposes, coarse-grained categorization is preferable.
  Let $\mathcal{R} = \{1, 2, ..R\}$ be the set of roles under consideration.
- *Units*: a unit is defined as the context in which ICT services are being used. For example, a unit could be a cost center group [35] (e.g., operating room), a cost center (e.g., operating room 1), a service-line [36] (e.g., orthopedics) or a department [37] (e.g., general surgery). The designer has to define units based on the organizational structure, available information, and space use. It is assumed that network nodes can be shared by multiple units.
  Let $\mathcal{U} = \{1, 2, ..U\}$ be the set of organizational units under consideration.

To apportion expected loss among network nodes using our dependency model, we propose a methodology inspired in the risk management process defined in NIST 800-39 [38] with the following steps:

1) **Framing**. This step establishes the context and provides a common perspective of the organization and ICT services in place. It takes inputs from both managerial and technical levels and produces the information used in subsequent steps.
   The output of this step is the specification of:
   - set $\mathcal{R}$: roles under consideration.
   - set $\mathcal{U}$: units under consideration.
   - set $\mathcal{P} = \{p_{jk}, j \in \mathcal{R}, k \in \mathcal{U}\}$: users by role and unit.
   - set $\mathcal{L} = \{l_j, j \in \mathcal{R}\}$: hourly labor cost by role.
2) **Impact assessment**. This step quantifies the expected loss when ICT services are down. We assume that staff with the same role and unit use the same set of ICT services. The expected loss is determined as follows:
   a) Define a set of levels of dependency that represent extra time needed to compensate for ICT disruption (including updating the information systems after recovery). For example, a level of 0.5 (*medium*) means that 50% of extra time is needed by a worker to do her job when ICT services are down. We assume that extra time directly translates to extra labor cost.
   b) Estimate the level of IT dependency for each unit and role using the scale previously defined.
   c) Determine the hourly extra labor cost attributable to ICT outage for each role and unit using the previous estimation and the labor cost by role from $\mathcal{L}$.

   The output of step 2 is:
   - set $\mathcal{E} = \{e_{jk}, j \in \mathcal{R}, k \in \mathcal{U}\}$ with the hourly loss attributable to ICT outage for each role and unit under consideration.
3) **Distribution of users among network nodes**. Specify units using each node. For each of such units, specify how many users from each role are attached to the node. Let us define the boolean variable α_{ijk} be 1 if a user from role j and unit k is attached to node i and 0 otherwise.
   The output of this step is:
   - set $\mathcal{O} = \{o_{ijk}, \forall i \in N, \alpha_{ijk} = 1\}$. Where o_{ijk} is the number of users from p_{jk} that are wired to node i.
4) **Calculate S_i**. The expected loss rate associated with node i can be readily calculated by adding, for each unit using the node, the number of users from each role (from step 3) multiplied by their corresponding hourly loss (from step 2).

$$S_i = \sum_{j \in \mathcal{R}} \sum_{k \in \mathcal{U}} e_{jk} o_{ijk} \tag{11}$$

Let us illustrate the procedure with a simplified example that uses the network topology from Figure 2.

- output of step 1:
  - set of roles:
    $\mathcal{R} = \{\text{practicist}(r_1), \text{nurse}(r_2), \text{technician}(r_3)\}$.
  - set of units:
    $\mathcal{U} = \{\text{outpatient}(u_1), \text{radiology}(u_2), \text{surgey}(u_3)\}$.

[2] Although we are aware that this assumption is not accurate, it suffices for our needs (we consider average values) and simplifies the model.

TABLE 1. Hourly expected loss per role and unit (set $\mathcal{E}$).

	roles ($\mathcal{R}$)		
Unit ($\mathcal{U}$)	Practicist (r_1)	Nurse (r_2)	Other (r_3)
outpatient (u_1)	50€/h (medium)	15€/h(low)	50€/h (high)
radiology (u_2)	25€/h (low)	15€/h(low)	25€/h (medium)
surgery (u_3)	0€/h (null)	15€/h(low)	25€/h (medium)

TABLE 2. Distribution of users among network nodes (set $\mathcal{O}$).

		roles ($\mathcal{R}$)		
node i	unit ($\mathcal{U}$)	# Practicist(r_1)	# Nurse(r_2)	# other(r_3)
1	outpatient (u_1)	12	10	4
	radiology (u_2)	4	6	3
2	outpatient (u_1)	6	8	2
	surgery (u_3)	4	8	2
3	outpatient (u_1)	6	8	2

- set of users by role and unit:
  $\mathcal{P} = \{24(r_1u_1), 4(r_1u_2), 4(r_1u_3), 26(r_2u_1), 6(r_2u_2), 8(r_2u_3), 8(r_3u_1), 3(r_3u_2), 2(r_3u_3)\}$
- cost of labor:
  $\mathcal{L} = \{100\,€/h(l_1), 60\,€/h(l_2), 50\,€/h(l_3)\}$.

• output of step 2:
  - levels of dependency: 0 (null), 0.25 (low), 0.5 (medium), 1 (high).
  - hourly expected loss per role and unit (set $\mathcal{E}$ represented as Table 1 for better readability).

• output of step 3:
  - distribution of users among network nodes (set $\mathcal{O}$ represented as Table 2 for better readability).

• Step 4: Calculus of S_i. The expected hourly loss rate for each node (but the root) is calculated according to Equation 11 using the output of steps 2 and 3 as:

$$S_1 = 1\,215\,€/h$$
$$S_2 = 690\,€/h$$
$$S_3 = 520\,€/h$$

Now we have all terms in Equation 9 (recall from previous section that $\Gamma_i = 0.001$ and nodes were expected to be down 8.759 hour/year). Therefore, the expected loss from network outages after $T = 10$ years with an annual discount rate of 2% ($k = 0.02$) would be:

$$mLE(\boldsymbol{x}, T) = \sum_{j=1}^{10} \frac{8.759 \cdot 1\,215 + 8.759 \cdot 690 + 8.759 \cdot 520}{(1+0.02)^j} = 190\,795\,€$$

V. SOLUTION SEARCH METHOD

The solution to the optimization problem formulated in Section III-B requires finding the set of links that meet Equation 8. Therefore, the number of potential solutions increases with the number of nodes as $2^{|N|(|N|-1)/2}$ (see a complexity analysis in [27]). For this reason, exhaustive search (i.e. evaluating all potential topologies) is not usually feasible as N increases and heuristic search methods are commonly used as a general way to find a (semi) optimal solution.

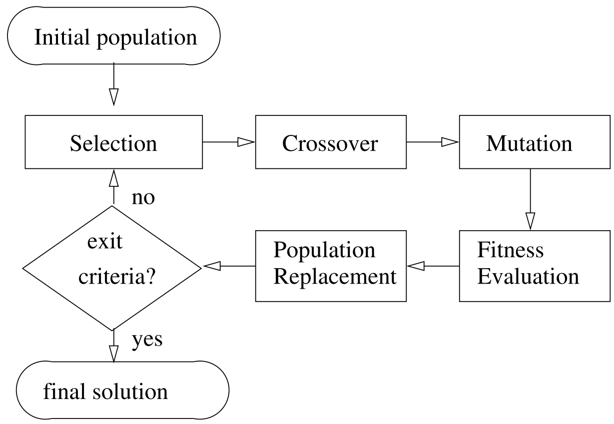

FIGURE 4. Main steps followed by our genetic algorithm.

Genetic Algorithms (GAs) were introduced in [39] and have demonstrated considerable success in providing good solutions to reliable network design problems as shown in [40]. Other metaheuristics, including particle swarms optimization, artificial immune system, and simulated annealing, can be used instead of or in hybridization with GAs. However, we opt for using well-known GAs for the sake of simplicity since: (a) their performance and quality of solutions in similar problems is already proven; (b) this work is not focused on the metaheuristic performance.

The performance of GAs can be improved by developing problem-specific heuristics in their operators. In this paper, we use the operations and heuristics proposed in [28] which are summarized here for the sake of completeness. Figure 4 shows the steps followed by our GA.

The operators used are:

- Initial Population and Population Size. Each individual is a topology $\boldsymbol{x}$. We create $|N|$ different individuals prone to be fit instead of random. To do so, we first create one individual with the lowest possible cost by solving the minimum spanning tree problem [41]. Then, we create $|N| - 1$ individuals that are the cheapest trees that differ from the first individual in only two links.
- Selection. We use proportional reproduction, ranking individuals by the fitness function defined in Eq. 8 corrected by a control parameter $f(x) = x^{\eta}$, $\eta < 1$ to avoid preferential parents selection, which could result in premature sub-optimal solutions.
- Crossover. The crossover operator combines characteristics of two parents to create two new individuals. We define a uniform-type crossover operation between parents A and B and descendants a and b as follows: each descendant is formed by selecting alternative pairs of links from each parent (e.g., a inherits from A links from nodes 0,1,3,4,7,8... and from B, links from nodes 2,3,5,6...)
- Mutation. The mutation operator adds randomness to the population. We develop an exchange-type mutation for each descendant, where for each pair of nodes

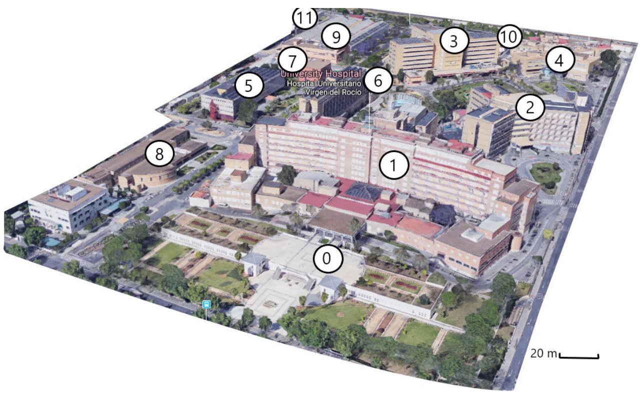

FIGURE 5. Nodes to be interconnected at hospital premises.

(i, j), x_{ij} is switched with probability P_m. Since topologies should be connected by definition, we eliminate new individuals not meeting this constraint after the crossover or mutation. We have checked that the percentage of new individuals born at each generation who do not meet this constraint is always below 1%.

- Fitness Evaluation. The fitness evaluation is based on the objective function in Eq. 8. The time complexity of this evaluation is $O\left(|L|^2|N|^2 \log^2(|L|)\right)$.
- Population replacement. The entire population by the $|N|$ better individuals from the present generation, including the newly descendants.

The algorithm finishes (exit criteria) when a new individual with lower fitness value can not be found after a certain number of generations. A study of the complexity and convergence speed of this algorithm can be found in [28].

VI. CASE STUDY: THE VIRGEN DEL ROCIO HOSPITAL

In this section, we apply our methodology to design the campus network of a large hospital. In order to make it replicable, we only use public information available at the time of writing such as the hospital's annual report [42], the hospital's IT Department report [43], or the regional health service annual report [44]. Managers with more detailed and accurate information will likely achieve better results.

Figure 5 illustrates the hospital campus and its main buildings.

Our goal is to find the best set of links that interconnect the nodes (i.e. buildings) in Figure 5 (campus-wide WAN network design) according to the optimization problem from Equation 8. It is assumed that the local area network topology within each building is predetermined by infrastructure design.

A. INTRODUCTION TO THE HOSPITAL ENVIRONMENT

The Virgen del Rocío hospital campus is located in Seville, Spain. It comprises 12 main buildings over an extension of 230 000 m^2, serving a population of nearly 600 000 inhabitants (inpatients, outpatients and emergencies). It counts with 54 operating rooms, 1 291 beds, and more than 5 000 workers categorized as physicians or nurses, plus 2 000+ non-clinical workers. From its annual budget of 516 M€ (2016), nearly 253 M€ correspond to labor cost.

Its IT Department coordinates services, including [45]:

- A data center with a server farm capable of dealing with more than 600 concurrent users for locally hosted services.
- Support and maintenance for applications, printers, servers, databases, firewalls, and website.
- The wired data network, composed of some 160 Ethernet switches, interconnecting more than 7 000 users, 3 000 client computers and 100 servers. It also provides access to the Internet and external ICT services.

The regional health service claims that the following corporate services are running in all regional public hospitals:

- Electronic Health Record (EHR) system. This software includes specialized modules for appointment and referral management, hospital outpatients, hospitalization, medical tests, emergency management, and electronic prescription [46], [47].
- Imaging Diagnostic System (IDS)
- Radiological Information System (RIS)
- Picture Achieving and Communication System (PACS)

Other systems reported [48], [49] but not included in the previous list are: Hospital Pharmacy Management, Human Resources Information, Hospital Accounting Information, Strategic Management Information, Voice over IP, kitchen management, band printing for patient identification, chronic patient management, inter-hospital information system, intranets, etc. It is expected that these systems are managed and hosted by the IT department.

In summary, several ICT services (either locally or remotely hosted) support business processes on campus, and hundreds of users depend on the wired data network to have access to them.

B. NETWORK NODES

As shown in Figure 5, the campus comprises 12 buildings (notice that node 0 is the root node). For our design, network nodes are placed at buildings' centroid as shown in Figure 5. Table 3 shows the set of nodes N with a brief description of each node and the shortest distance between them. This distance will be used to estimate the cost of each link in the optimization problem.

C. HOURLY EXPECTED LOSS PER NODE (S_i)

Using the methodology provided in Section IV-B, the following outputs are produced:

1) **Framing**. Human resources are classified in [42] as: high-management, medical practitioners, nursery, management and services, and residents. The number of workers and labor cost for each category are also provided. Based on this information, we have defined the roles (set $\mathcal{R}$) shown in Table 4 where we also

TABLE 3. List of network nodes and shortest distance.

		distance to node (m)											
node	description	0	1	2	3	4	5	6	7	8	9	10	11
0	Data center & Internet (root node)	-	68	213	319	373	220	186	282	148	399	399	483
1	General Hospital	68	-	146	252	305	177	129	231	143	339	333	426
2	Rehabilitation Hospital	213	146	-	133	160	185	121	194	235	246	206	343
3	Women's Hospital (obstetrics and gynecology)	319	252	133	-	107	178	151	137	279	120	80	217
4	Children's Hospital (pediatrics)	373	305	160	107	-	278	236	243	367	200	104	286
5	Diagnostics Center	220	177	185	178	278	-	66	69	115	202	246	271
6	Labs building	186	129	121	151	236	66	-	103	131	214	228	298
7	Anatomy pathology	282	231	194	137	243	69	103	-	184	133	190	203
8	Government building	148	143	235	279	367	115	131	184	-	316	354	382
9	Resource Management building (maintenance)	399	339	246	120	200	202	214	133	316	-	103	97
10	Laundry	399	333	206	80	104	246	228	190	354	103	-	182
11	Kitchen	483	426	343	217	286	271	298	203	382	97	182	-

TABLE 4. Personnel categories and labor costs.

Set $\mathcal{R}$	Role	Set $\mathcal{L}$ (€/hour)	#workers
$1(r_1)$	physician & managers	24.00	1 679
$2(r_2)$	nursery	16.00	4 203
$3(r_3)$	services & technicians	15.00	1 463
$4(r_4)$	administratiion	14.00	663

TABLE 5. Units considered.

Set $\mathcal{U}$	Unit description
1 (u_1)	hospitalization (in-patients)
2 (u_2)	surgery
3 (u_3)	intensive care
4 (u_4)	out-patient healthcare
5 (u_5)	image and labs
6 (u_6)	pharmacy
7 (u_7)	non-clinical services

show the hourly salary per role (set $\mathcal{L}$), and the number of workers that belong to each role despite their unit ($p_j = \sum_{k \in \mathcal{U}} p_{jk}$)

The first role includes not only physicians but also high-management, residents and pharmacists. In general, any highly qualified (e.g., master's or doctoral degree or equivalent) position. The second role includes both nurses and nurse's aides. The third role includes healthcare support workers such as ancillaries, clinical support staff, therapy assistants, etc. and domestic-related personnel (e.g., cook, housekeepers, maintenance). Finally, the last role includes only administrative personnel (i.e. clerks, receptionists, secretaries). The estimated cost of labor shown in the third column of Table 4 is aligned with the information available in the annual report, adding up to ≈210M €/year (only regular hours). This represents about 136 000 €/hour.

Regarding the units to be considered, the hospital annual report unveils three different organizational schemes:

- Five clinical areas: hospitalization, surgery, emergencies, out-patients, and obstetrics.
- Forty clinical management units (e.g., allergy, pathological anatomy, ophthalmology, intensive care, pediatric intensive care, general surgery, pediatric surgery, pharmacy, labs, internal medicine, etc..). In [50] one can find further information about each unit such as personnel and categories, resources, budget, and activity performance metrics in the areas of hospitalization, surgery, and out-patient.
- Thirty-five service lines (e.g., critically burned, rare neuromuscular illnesses, rare cancers, etc..).

For the purpose of network design, we define a simple combination of clinical areas, some clinical units, and other non-clinical departments as shown in Table 5.

Various iterations were necessary to sort-out a definite list of units. For example, administration was first suggested as a unit, but after studying available information we realized that it was a role that all units had. Precisely, available information influenced our final choice (e.g., clinical units activity, and resources are broken down by areas similar to $u_1 - u_4$ in [50]).

2) **Impact assessment**. We define the same levels of ICT dependency as in our previous example: 0 (null), 0.25 (low), 0.5 (medium), 1 (high).
Table 6 shows the estimated hourly loss for each role and unit under consideration (set $\mathcal{E}$). Basic knowledge of the activity and typical ICT services used by each unit is required to make an accurate judgment. For example, administrative work is likely to be more impaired than those services based on manual work (e.g., cleaning, transporting patients), or that a physician will be more impaired by lack of ICT services during an out-patient visit than during a surgery procedure. Documents such as disaster recovery plans can provide useful information about the impact of outages, manual procedures, etc.

3) **Distribution of users among network nodes**. Although this step is straightforward with the proper information, this is not the type of information publicly available. We have undergone a careful examination of each clinical unit listed in [50], its resources, personnel, and activity. The main assumptions made are:
   - A 5% rate of absenteeism has been considered as stated in [42].

TABLE 6. Hourly lost profit per category and unit (set $\mathcal{E}$).

unit	r_1 €/h	r_2 €/h	r_3 €/h	r_4 €/h
u_1	6 (low)	4 (low)	3.75 (low)	14 (high)
u_2	6 (low)	4 (low)	-	3.5 (low)
u_3	6 (low)	4 (low)	-	14 (high)
u_4	12 (medium)	4 (low)	-	14 (high)
u_5	24 (high)	16 (high)	7.5 (medium)	14 (high)
u_6	24 (high)	16 (high)	7.5 (medium)	14 (high)
u_7	12 (medium)	8 (medium)	-	7 (medium)

TABLE 7. Distribution of users among network nodes (set $\mathcal{O}$).

node (i)	units	r_1	r_2	r_3	r_4
1	u1	157	646	42	45
	u2	92	171	8	7
	u3	34	223	34	17
	u4	348	314	19	55
	u6	22	20	10	5
	u7	4	8	28	7
2	u1	14	83	9	4
	u2	10	31	4	1
	u3	20	127	24	13
	u4	28	9	1	1
3	u1	14	114	20	13
	u2	9	33	3	1
	u3	12	64	14	3
	u4	40	24	4	16
4	u1	29	173	10	5
	u2	7	18	2	1
	u3	11	76	3	3
	u4	68	67	4	6
5	u5	61	135	15	22
6	u4	25	81	5	8
7	u2	23	4	28	1
	u5	8	1	8	9
8	u7	15	7	14	182
9	u7	1	14	102	14
10	u7	0	1	49	1
11	u7	0	1	210	3

- Shifts have been taken into account. Workers have been distributed among shifts according to their unit and role.[3] For example, more nurses than doctors are expected to do the night shift in the hospitalization unit.
- The most-loaded morning shift (see Table 7) is extrapolated. As a consequence, worst-case scenario is considered and our final solution might be conservative (i.e. rates S_i could be overdimensioned).

Table 7 shows the distribution of personnel among network nodes.

4) **Calculate** S_i. The expected loss rate for every node (but the root) can be readily calculated using Tables 7 and 6 as indicated by Equation 11. Coefficients S_i are shown in Table 8. According to the values obtained, the lack of ICT services in the entire campus would have a negative impact of about 21% of labor cost.

[3]We have followed a heuristic approach to determine how different roles and units are distributed among shifts. However, high management is expected to handle more accurate numbers.

TABLE 8. Hourly expected loss rate estimated for each node S_i.

node (i)	r_1	r_2	r_3	r_4	S_i (€/hour)
1	6 459.60	5 789.64	232.05	1 786.52	14 267.81
2	601.69	998.76	34.13	253.92	1 888.50
3	691.50	940.80	76.39	453.25	2 161.94
4	1 101.91	1 336.80	38.18	194.90	2 671.79
5	1 462.50	2 162.16	14.56	21.84	3 661.06
6	600.00	1 295.84	4.55	8.19	1 908.58
7	318.60	39.20	8.40	10.50	376.70
8	182.40	56.00	-	1 274.00	1 512.40
9	9.60	112.00	-	98.00	219.60
10	-	5.60	-	4.90	10.50
11	-	5.60	-	19.60	25.20

Note that S_i roughly reflects which nodes are more important for a specific organization in terms of productivity. This is a crucial difference with respect to current reliable-network topology design problems. In our case, it is clear that the most important node is 1 whereas nodes 7, 9, 10 and 11 are the least important.

VII. RESULTS

In this section we find the best topology for the Virgen del Rocio hospital campus network by solving our optimization problem as described in Section V. For the remainder of the section, this problem will be regarded as the Hospital Campus Reliable Network Design (HC-RND) problem. Since our HC-RND problem includes the period over which the expected loss is accounted for (parameter T), we will solve it for two periods: one year and three years (with an annual discount rate of 2%). Then we compare the solutions obtained with two common cost-effective topologies:

- The minimum-cost tree topology: it is the tree (i.e. no redundant links) which exhibits the lowest CAPEX. This is obtained by solving the Minimum Spanning Tree problem [41].
- The minimum-cost ring topology: it is the ring (i.e. one redundant link) which exhibits the lowest CAPEX (i.e. that minimizes the total ring length). This is obtained by solving the classical Traveling Salesman Problem [51].

A. PARAMETERS USED

Cost-related information is required to solve either of the problems included in this section. But solving the HC-RND problem also requires setting additional parameters of the reliability model from Section IV-A, and for the genetic algorithm from Section V.

1) COST PARAMETERS (c_{ij})

We have consider a fixed cost of 7 500€ per link, and a variable cost of 50 €/meter (civil work included) for the procurement of communication links. Considering the distances in Table 3, the CAPEX has a lower bound of 136 750 € (minimum cost tree topology with 11 links) and an upper bound of 1.2M € (maximum cost full-mesh topology, with 66 links).

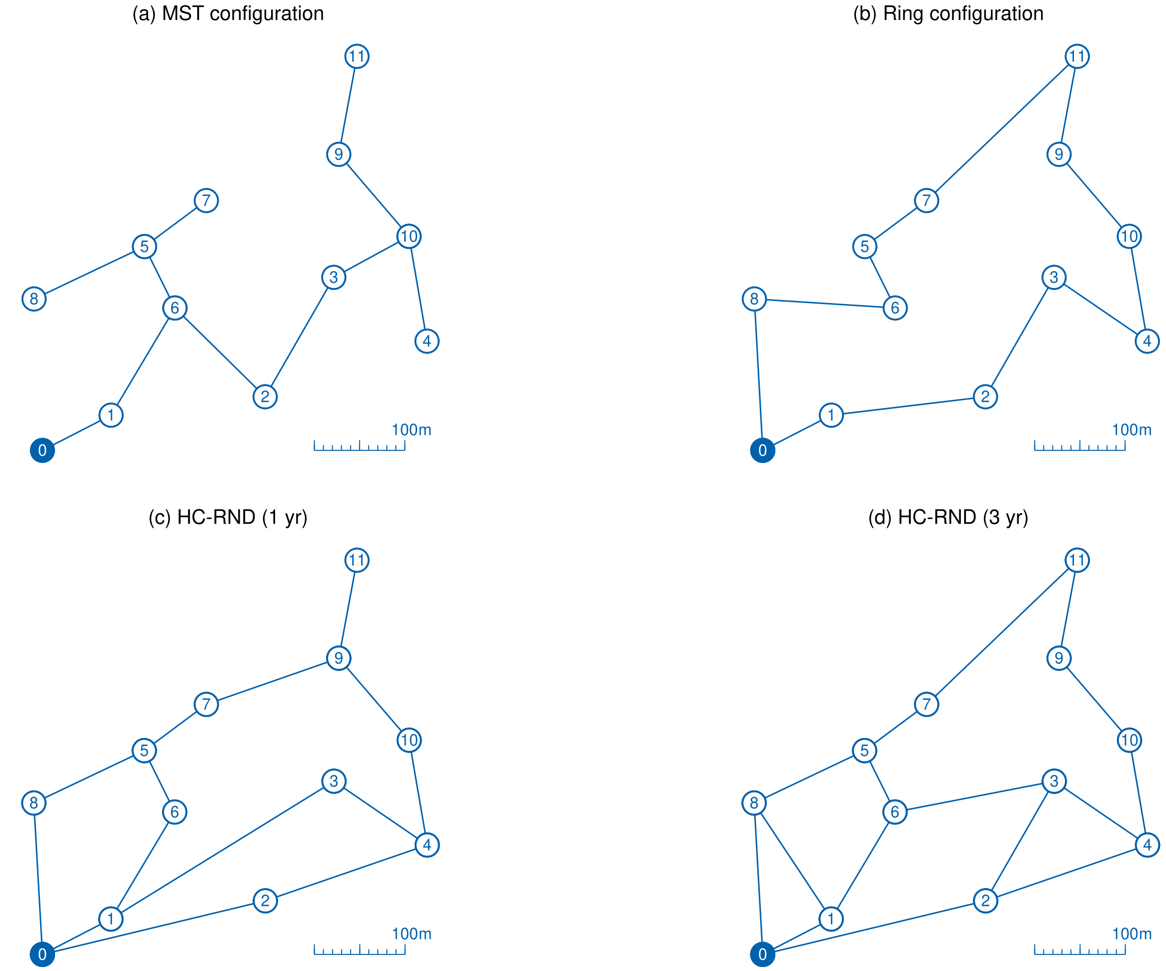

FIGURE 6. Topologies obtained.

2) RELIABILITY MODEL PARAMETERS (p_n, p_l)

We have considered that up to two nodes and four links could simultaneously fail ($N_F = 2, L_F = 4$) with a rate of $9.\overline{3} \cdot 10^{-4}$ per hour (equivalent to 8 h/year) and $2.74 \cdot 10^{-5}$ per meter and hour respectively. Using these values, the minimum cost tree topology would exhibit a reliability of 0.944379.

3) GENETIC ALGORITHM

The parameters used in the genetic algorithm are the following:

- Initial Population: ($|N| = 12$)
- Selection: control parameter $\eta = 0.01$.
- Crossover and mutation rates: 0.6 and 0.05 respectively.
- Exit criteria: no better individuals found after 1 000 generations.

B. EVALUATION OF THE TOPOLOGIES OBTAINED

Table 9 shows the topologies obtained. For each topology, the second column shows the network reliability (i.e. the average probability that nodes can reach the root); the third column shows the CAPEX of the network; the fourth column represents the annual modified loss expectancy; and the last column shows the number of links in the topology. These topologies are represented in Figure 6.

TABLE 9. Topologies under study: Results obtained.

	Reliability	CAPEX (€)	mLE (€)	links
minimum-cost tree	0.944379	136 750	7 570 024	11
minimum-cost ring	0.997367	158 900	409 227	12
HC-RND (T=1yr)	0.998647	193 350	16 994	14
HC-RND (T=3yr)	0.999826	220 550	3 013	16

The last column from Table 9 shows that the four topologies exhibit a low number of links (between 11 and 16 out of a maximum of 66). This explains that the network cost (third column) lies in the bottom 7% of the range in all cases. In spite of that, there are notable differences between the cheapest topology and topologies from the HC-RND problem, which are 41% (T=1yr) and 61% (T=3yr) more expensive than the minimum-cost tree. However, if one examines the annual expected loss (fourth column) saved as a result of higher reliability it can be concluded that the extra cost invested in redundancy pays off, particularly in large organizations such as hospitals where cost of labor is very high (note that mLE associated with the minimum-cost topology is only ≈2% of labor cost). For example, after one year of network operation, HC-RND(1yr) reduces loss expectancy in more than 95% (+392 000€) with respect to the minimum-cost ring with an extra cost of only 34 450€ (21% more). Interestingly, both topologies exhibit a comparable network reliability figure. This shows that similar values of network reliability can translate to disparate benefits in terms of expected loss saved. This reflects the need to use meaningful indicators for managers besides reliability.

Extending the period over which lost profits are accounted for increases loss expectancy as a result of longer accumulated network downtime. As a consequence, the HC-RND problem reacts increasing reliability (and cost) to reduce mLE. This can be seen in HC-RND(T=3yr). After 3 years of network operation HC-RND(T=1yr) accumulates a expected loss of 50 982 € while HC-RND(T=3yr) only accumulates 9 039 €. The 41 943 € difference saved outweighs a cost increment of 27 200 €. Unfortunately, the minimum-cost tree and minimum-cost ring problems do not consider any time horizon as a part of the problem definition therefore, the benefit of HC-RND becomes even more apparent. We believe that it is useful to consider a time horizon as part of the problem definition just like with any other investment.

The topologies from Figure 6 show how nodes with higher value of S_i (see Table 8) such as 1, 4, and 5, exhibit more links than those with lower value (e.g., 7, 10, 11). Comparing topologies (c) and (d) reveals how higher T produces more reliable networks (i.e. with more alternative physical paths to the root node).

VIII. CONCLUSION AND FUTURE WORKS

The wired data network plays a crucial role in organizational productivity not modeled in traditional topology design problems. We have proposed an optimization problem and a methodology for the design of a cost-effective reliable network suited for hospital environments. Our problem is founded on the principles of risk analysis and finds the most profitable topology considering the cost of building the network, and the impact of network downtime in productivity.

A case study illustrates the benefits of our proposal. The expected lost profits saved with HC-RND topologies is multiple times greater than that of minimum-cost topologies, which outweighs higher capital expenditure. This is particularly important in a large organization where the cost of labor exceeds 200M€/year.

The HC-RND problem and our suggested methodology should help network engineers and hospital management to be aware of the consequences of network incidents, use common terms understandable by both parts, and make better investment when (re)designing data networks.

Some open issues can be identified for further research. For example, a decentralized approach where services were not delivered through a central node could be studied. This would require the definition of extra information about users and nodes. Based on this information, the reliability model would have to be adapted from a two-terminal to a n-terminal model as well as $mLE(x, T)$ which would have to account for the availability of each service. Another issue to be explored is correlated failures, which would directly impact the reliability model as it would have to include now a correlation model according to the problem studied (e.g., power failure, cyberattack, etc.).

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